THE FOUR STAGE HELIA EXPERIMENT*

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Abstract

A four stage, 4 MV, 250 kA, 30 ns accelerator to demonstrate the High Energy Linear Induction Accelerator (HELIA) concept is described. HELIA uses modular, water dielectric, pulse forming lines to drive inductively isolated cavities. A cathode stalk extends the length of the accelerator, adds the voltages from the cavities, and delivers the power to a high voltage anode-cathode gap. The cathode stalk constitutes the inner electrode of a coaxial magnetically insulated transmission line (MITL). The outer electrode of the MITL is not continuous but is interrupted at regular intervals by the cavity feeds. The single cavity experiment demonstrated the performance of individual cavities and pulse forming elements. The four cavity experiment demonstrated the key physics issues of the HELIA concept. The design and performance of the pulsed power driver, induction cavities, and measurements of the power delivered by the MITL to an electron beam load are presented.

1.0 Introduction

High power pulsed accelerators are of special interest to particle beam generation and nuclear weapons effects simulation. In Proto-I[1], Proto-II[2], and PBFA-I[3] modular systems have been arranged in parallel to form low voltage, high current drivers. In linear induction accelerators such as ATA[4] and RADLAC[5], an electron beam is accelerated through several stages, each of which is powered by a modular pulsed power driver. The drifting electron beam thus adds the voltages of the individual stages. The injector for these accelerators consists of two or more stages arranged in series. A cathode stalk extends the length of the injector in RADLAC II and forms a gap with the anode where the electron beam is generated. In ATA a re-entrant anode stalk forms a gap when it meets the cathode stalk. The voltage across this anode-cathode gap is the sum of the voltages in the injector stages. Each stage in ATA accelerates a 10 kA, 70 ns beam through 250 kV. This beam is generated in an injector section consisting of ten stages arranged in series. One of the authors (I. D. Smith) suggested[6] that the technology of the ATA injector could be extended to much higher powers. The HELIA experiments grew out of this suggestion and a subsequent study funded by the Defense Nuclear Agency[7] as a joint DOE/DNA technology demonstration program. A description of the HELIA concept, the individual components, and results of the single cavity experiment were presented in a paper by D. E.

Hasti et al.[8] That experiment demonstrated the performance capabilities of the individual system components. The four stage experiment was intended to demonstrate the key physics issues of the HELIA concept.

2.0 The Four Stage Experiment

A drawing of the four stage experiment is shown in Figure 1. Four inductively isolated cavities are coupled in series. Each of these cavities passes a 1 MV, 250 kA, 30 ns pulse delivered by pairs of pulse forming lines (PFLs). A long cathode stalk extends the length of the four cavities and forms the inner conductor of a coaxial MITL. The outer conductor of the MITL is formed by the bore of the cavities. In ATA the fields are low enough that the current flows along the surface of the cathode stalk. In HELIA the fields are high enough to have electron emission from the cathode stalk. The voltage addition occurs along the stalk, and in order to have efficient operation, the emission from this stalk must be trapped; i.e. the adder section must operate as an efficient MITL. This is an unusual MITL in that the outer (positive) conductor of the coax is periodically interrupted by the feeds from the individual cavities. The inner (negative) conductor is tapered as shown. The design of this MITL and the simulations that were made using the particle-in-cell code MAGIC[9] are described in Ref. 8. This experiment was designed to verify efficient operation of the MITL as predicted by the code simulations.
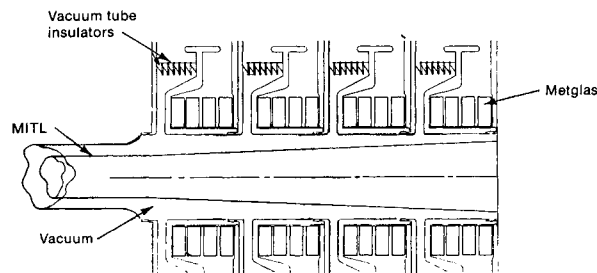

Figure 1. Drawing of four stage MITL adder section.

2.1 Energy Store and Slow Pulsed Power

The energy storage section for this experiment consists of two and a half rows of a PBFA-I type Marx generator which uses 20, 1.3 µF capacitors. At full charge the Marx stores 130 kJ. The open circuit voltage is 2.0 MV. The intermediate energy store (I.S.) consists of two, 7.5 nF water capacitors similar to those used on Proto II and arranged in parallel. A 5Ω series resistor was added to the circuit to absorb the excess energy which results because of the large capacitive mismatch between the

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14. ABSTRACT
A four stage, 4 MV, 250 kA, 30 ns accelerator to demonstrate the High Energy Linear Induction Accelerator (HELIA) concept is described, HELIA uses modular, water dielectric, pulse forming lines to drive inductively isolated cavities. A cathode stalk extends the length of the accelerator, adds the voltages from the cavities, and delivers the power to a high voltage anode-cathode gap. The cathode stalk constitutes the inner electrode of a coaxial magnetically insulated transmission line (MITL). The outer electrode of the MITL is not continuous but is interrupted at regular intervals by the cavity feeds. The single cavity experiment demonstrated the performance of individual cavities and pulse forming elements. The four cavity experiment demonstrated the key physics issues of the HELIA concept. The design and performance of the p~lsed power driver, induction cavities, and measurements of the power delivered by the MITL to an electron beam load are presented.

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Marx and the intermediate energy store. The energy in the I.S. is transferred to the PFLs via oil transmission lines by a self-breaking gas switch. Figure 2 is a photograph of the slow pulsed power section.
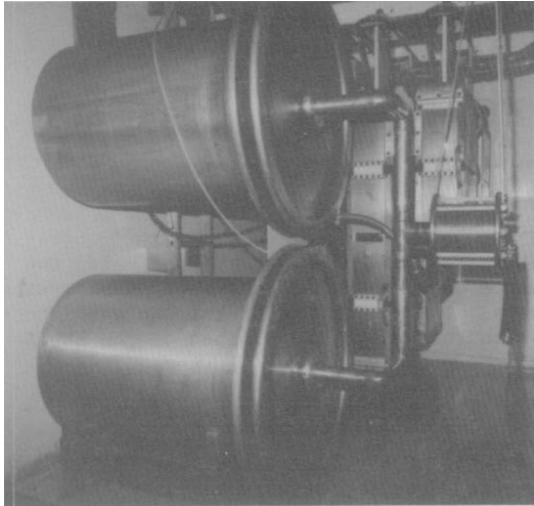

Figure 2. Photograph of slow pulsed power section.

2.2 The Pulse Forming Lines

The water dielectric PFLs are charged by the I.S. via coaxial oil dielectric transmission lines. There are eight PFLs grouped in pairs arranged top and bottom. Each pair feeds one inductive cavity. The PFLs are 8Ω, 15 ns (one-way transit) coaxial lines and are charged to a maximum voltage of 2.0 MV in about 170 ns. These lines are of similar design to those used in the single cavity experiment and described in Ref. 8. A typical output waveform produced by the PFLs is shown in Figure 3. The fast collapse at the trailing edge of the pulse is due to the closing of the crowbar switch. The output pulse would be longer than the 30 ns of the PFL due to the energy stored in the high voltage oil distribution lines and which feeds through in the time of interest. The first to last time spread between the eight output pulses was typically 8 to 10 ns. Once, shortly after recirculating the deionized water in the PFLs, the switch jitter became significantly worse. This behavior is not fully understood. New switch designs are being investigated to further stabilize the output switch jitter. The PFLs are equipped with self breaking water peaking gaps. This design provides a capability to further reduce the rise time of the pulses injected into the cavities. The performance of the peaking gaps have not been fully tested and the proof-of-principle experiment was performed with the peaking gaps fully closed. Several hundred systems shots were accumulated during the performance of the experiment, several dozen of which were at or near full power. The system was disassembled for a thorough inspection after the experiment. No evidence of any arcing or any tracking of the oil/water interfaces or insulator supports were found. The open stacks located directly above the switches provide access to the switches and a pressure relief for the water shocks generated when the switches close. The aluminum welds around these stacks failed after a few hundred system shots. A new design based on cylindrical stacks and stainless steel construction is being implemented to resolve this mechanical limitation.
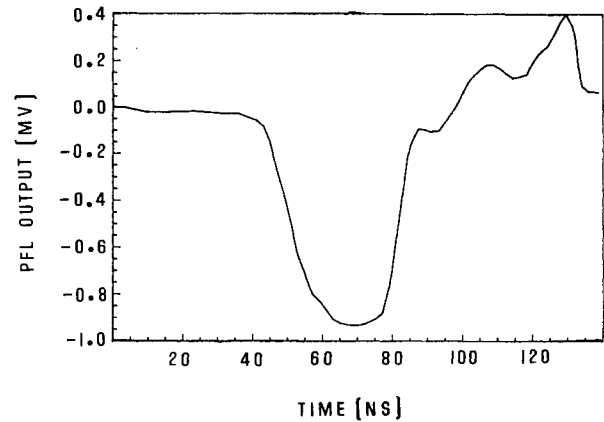

Figure 3. Typical output waveform produced by PFLs.

2.3 The Inductive Cavities

A cross sectional drawing of an inductive cavity is shown in Figure 4. A detailed description of the design of these cavities is given in Ref. 8. The oil impregnated Meglas cores were specially developed for HELIA. The oil dielectric annular transmission lines mix the input from the two PFLs and transform them into a four point feed at the high voltage ring just outside of the cores and vacuum insulator stack. Each of these four points has an equal contribution from both PFLs. Low voltage injection tests indicate that this design gives a symmetric feed at the cavity bore to within 5%. It is not clear at present that this degree of symmetry is necessary for efficient operation of the adder MITL. Should it prove unnecessary, the removal of these lines would significantly reduce the complexity and cost of the cavities.
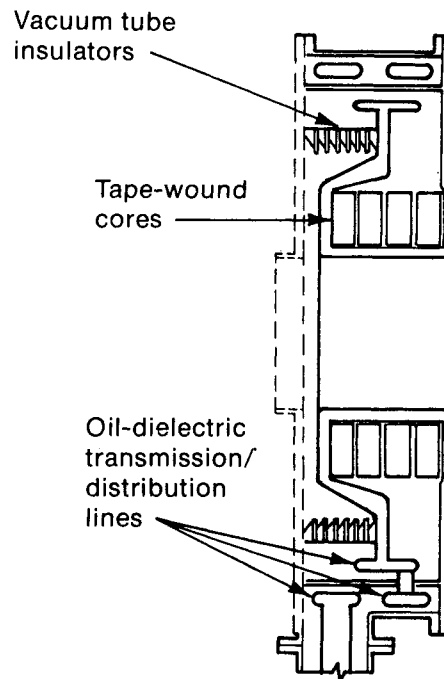

Figure 4. Cross section of inductive cavity.

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2.4 The Adder MITL

The MAGIC code calculations that aided in the design of the MITL were described in Ref. 8. In these calculations the negative (inner) electrode of the MITL had discrete radial steps to vary the free space impedance of the line in an 8Ω-15Ω-21Ω-28Ω sequence at the location of the four cavities. The cathode for the MITL used in this experiment was a cone that continuously transformed the impedance from 8Ω to 28Ω. These parameters were chosen assuming a 250 kA e-beam load at the end of the adder MITL.

3.0 The Experimental Configuration

Figure 1 shows the layout of the adder section used in the experiment, except that the MITL only extended ~10 cm past the last cavity and terminated in an e-beam diode with an annular blade cathode. Each cavity had voltage and current monitors to record the waveforms just outside of the insulator stack. A segmented Rogowski coil measured the total diode current and a vacuum voltage monitor (VVM) measured the voltage across the actual anode-cathode gap. Figure 5 is a photograph of the four stage HELIA experiment.
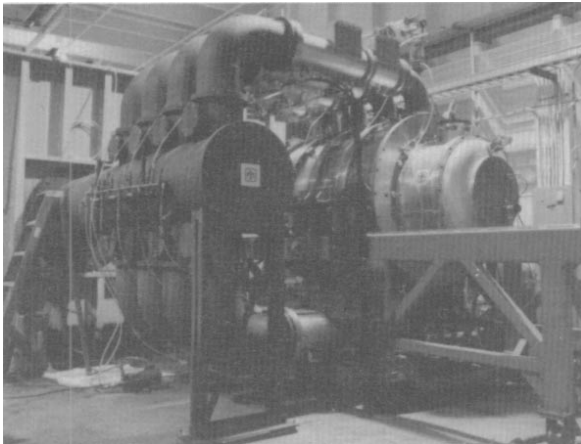

Figure 5. Photograph of four stage HELIA experiment.

4.0 Experimental results

The HELIA adder, when operating at 100% efficiency, could be characterized as a source with a 16Ω source impedance (four times the source impedance driving each cavity) and a maximum open circuit voltage of 8 MV (four times the open circuit voltage driving each cavity). A load line for the HELIA adder was determined by varying the diode impedance. Figure 6 shows a typical set of input waveforms from the PFLs. Figure 7 shows the corresponding waveforms for the VVM and diode Rogowski. The load line obtained for this set of input parameters is shown in Figure 8. The solid line is a 16Ω load line drawn through the data points. The error bars on the data points represent the uncertainty in the calibration of the diode monitors. The shaded diagonal band represents the load line that would correspond with this data if the adder MITL was operating at 100% efficiency. The width of this band represents the uncertainty in the calibration of the PFL output monitors. These data are consistent with adder operating efficiencies between 87% and 100% as defined by the source open circuit voltage. Other data support this conclusion. No evidence of arcing was found inside the cavities or the PFLs. Within experimental uncertainties, the same amount of current flowed through the cavities and diode as would be expected for efficient operation, since these elements are all in series. Similarly the sum of the voltages measured at the cavities is consistent with the voltage measured by the VVM. No evidence for core saturation was seen during the main pulse. The adder operated in the same consistent way for average input voltages from ~400 kV to ~1 MV. The VVM failed for diode voltages greater than ~2.7 MV. Above this level we were unable to get a direct measurement of the voltage at the diode. Other supporting data, such as those mentioned above plus radiation measurements, strongly indicated high operating efficiency for the adder.
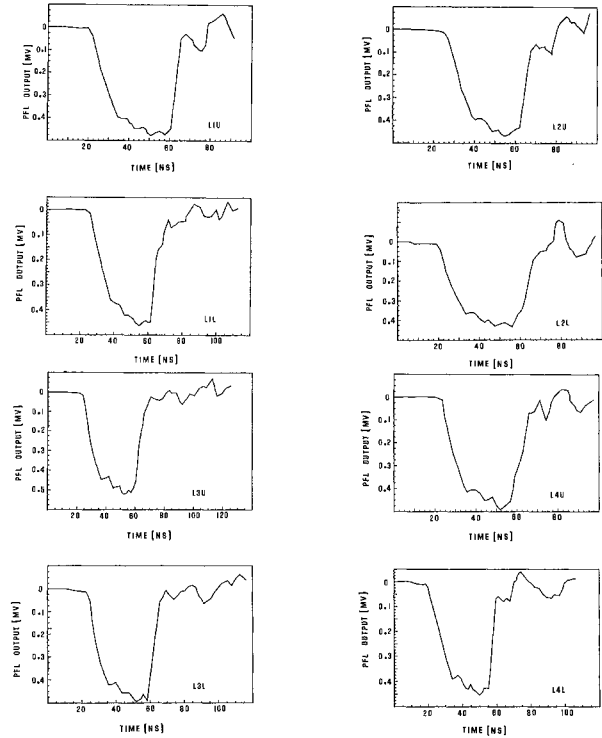

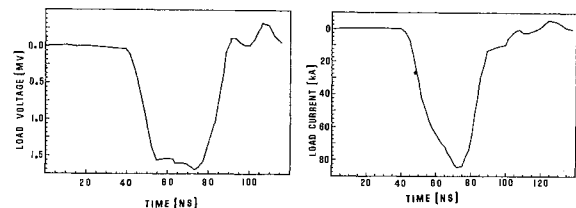Figure 6. Typical set of input waveforms from PFLs.

Figure 7. Diode voltage and current waveforms corresponding to input waveforms shown in Figure 6.
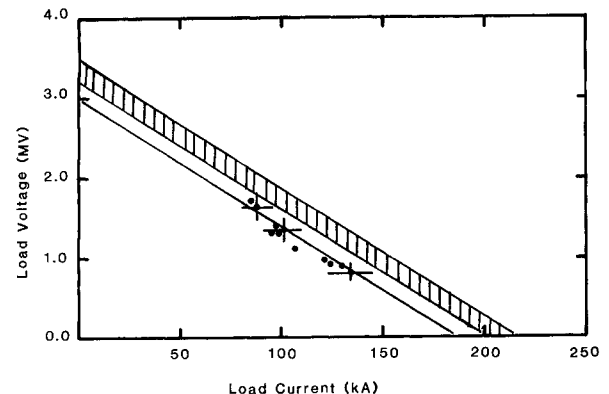

Figure 8. HELIA load line obtained by varying diode impedance.

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5.0 Summary and Conclusions

The four stage HELIA experiment has been completed. This was a "proof-of-principle" test to show that the inductively isolated cavity adder concept can be extended to much higher power levels and accelerator gradients by using magnetic insulation and Meglas cores. In HELIA each cavity is fed by two PFLs and passes a 1 MV, 250 kA, 30 ns pulse. At full power the four cavity accelerator delivers 4 MV, 250 kA, 30 ns to an e-beam load. Aside from the design and construction of the inductive cavities and their drivers, the main new physics issue investigated is the performance of the cathode stalk as an efficient MITL. Results indicate that the MITL adder section is between 87% and 100% efficient.

The four cavity experiment has demonstrated the key physics issues of the HELIA concept. The concept can be extended to higher power levels then achieved in this experiment. The limitations of this technology are not clear at present and need further investigation. The MITL performance may be different when the load is transit time isolated from some sections of the MITL adder. Preliminary MAGIC calculations indicate that efficient voltage addition can still be obtained for this case.

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